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Adaptive Radar Data Quality Control and Ensemble-Based Assimilation for Analyzing and Forecasting High-Impact Weather

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LONG-TERM GOALS

Study and develop advanced approaches for radar data quality control (QC) and assimilation that will not only optimally utilize Doppler wind information from WSR-88D and Terminal Doppler Weather Radar (TDWR) but also take full advantage of rapid and flexible agile-beam scans from the phased array radar (PAR) at NWRT.

OBJECTIVES

Develop advanced methodologies for radar velocity data QC and assimilation that will not only optimally utilize observations from operational Weather Surveillance Radar-1988 Doppler (WSR-88D) and Terminal Doppler Weather Radar (TDWR) but also take full advantage of rapid and flexible agile-beam scans from the phased array radar (PAR) at the National Weather Radar Testbed (NWRT).

APPROACH

Use the automated radar-based wind analysis system (RWAS, Xu et al. 2009) to monitor and record various data quality problems in operational WSR-88D and TDWR radar observations as well as NWRT PAR observations. Investigate and classify outstanding data quality problems, and develop advanced adaptive data QC techniques for various scan modes to satisfy data assimilation needs.

Extend the theoretical formulations derived for measuring information content from observations for data assimilation, so efficient data compression strategies and optimal PAR scan strategies can be designed based on the modern information theory to maximize the information content from observations and minimize data redundancy for ensemble-based radar data assimilation.

Explore and develop new hybrid sampling approaches based on Bayesian probability theory for ensemble-based radar data assimilation to improve real-time analysis and forecast of high-impact weather.

The PI, Dr. Qin Xu, is responsible to derive basic formalisms and provide technical guidelines for the implementations. The data collections and QC algorithm developments are performed by project-supported research scientists at CIMMS, the University of Oklahoma. Dr. Allen Q. Zhao at NRL

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Monterey and Dr. Shun Liu at NOAA/NCEP perform pre-operational tests as the radar data QC and assimilation packages are upgraded and delivered.

WORK COMPLETED

The previous AR-VAD analysis technique (Xu et al. 2010) was further developed into a two-step alias-robust variational analysis technique, called AR-Var (Xu and Nai 2012a, XN12a hereafter), to estimate the radial-velocity field beyond the VAD uniform-wind model from raw aliased radial-velocity observations on each range circle. This two-step AR-Var analysis can provide a reliable reference radial-velocity field for the reference check in radar velocity dealiasing even when the Nyquist velocity is reduced below 12 m s^{-1}. By using the AR-Var analysis in place of the AR-VAD analysis for the reference check, the previous AR-VAD-based dealiasing method (Xu et al. 2011a, X11a hereafter) was improved to an AR-Var-based dealiasing method adaptively for radar radial velocities scanned with small Nyquist velocities (Xu and Nai 2012b, XN12b hereafter). The real-time RWAS (Xu et al. 2009) was used to monitor the performance of the method by displaying the dealiased radial velocities and their produced wind in comparison with observations from other sources (Xu et al. 2011b).

In the previous AR-VAD-based dealiasing method (X11a) as well as the improved method (XN12b), the seed data produced by the reference check in the first step are free of false delousing but often have limited coverage (unless the raw data cover nearly the entire radial range on each tilt of radar scan as shown in Fig. 2a of XN12b for a typical winter ice storm). For spring and summer convective storms, the raw data are often scattered in storm areas, so the seed data produced by the reference check cover only a limited radial range on each tilt. To improve the dealiased data coverage, the block-to-point continuity check in the second step was upgraded from the original one-way procedure (going forward away from the radar) to a double two-way procedure (going forward and backward twice on each tilt) with additional sub-steps designed to recheck remaining flagged data around each mesocyclone (Xu et al. 2012c).

The information contents from radar observations for data assimilation were computed by using the spectral formulations of Xu (2011) and verified against the results computed accurately but costly from the singular-value formulations. The results demonstrated that the spectral formulations can be used (i) to precisely compute the information contents from one-dimensional radar data uniformly distributed along the radar beam, (ii) to approximately estimate the information contents from two-dimensional radar observations non-uniformly distributed on the conical surface of radar scan, and thus (iii) to estimate the information losses caused by super-observations generated by local averaging with a series of successively coarsened resolutions to find an optimally coarsened resolution for radar data compression with zero or near-zero minimal loss of information. As the background and observation error power spectra can be derived analytically for the above utilities, the spectral formulations are computationally much more efficient and affordable than the singular-value formulations, especially when the background space and observation space are both extremely large and too large to be computed by the singular-value formulations (Xu and Wei 2011).

Balanced dynamics can be used to constrain the background covariance implicitly to improve the analysis in data assimilation (Derber and Bouttier 1999). Balanced dynamics can be also used to constrain the analyzed field explicitly and thus improve the analysis directly. To facilitate this, the semibalance model (SBM) of Xu (1994) in pseudoheight-coordinates was re-derived in the same terrain-following coordinates as that used in the operational WRF model (Skamarock et al. 2008). As the potential vorticity is conserved and invertible for the nonlinearly-balanced primary flow and the

secondary flow can be solved diagnostically in the terrain-following coordinates, the re-derived SBM is suitable for analyzing balanced dynamics in real weather events, such as slowly-varying vortices and curved fronts (Xu and Cao 2012).

The RWAS (Xu et al. 2009) was upgraded to use background winds optionally from operational model forecasts in real time and to produce analyzed wind fields over an extended area by using radial velocities scanned from all the operational radars (plus Oklahoma Mesonet wind data) over the extended area (Xu et al. 2012c). A vortex wind analysis scheme was designed with flow-dependent background covariance, and it can be used as an additional analysis step in the RWAS to privide a new and much enhanced capability in nowcasting tornadic mesocyclones.

RESULTS

The new AR-Var-based dealiasing method (XN12b) was successfully tested with severely aliased velocity data (286 volumes) collected using VCP31 with v_N reduced below 12 m s^{-1} from the KTLX radar. The method was also successfully tested with aliased velocity data (127 volumes) collected from the FAA's TDWR (TOKC near the Oklahoma City Airport) using scan Mode80 with v_N reduced below 15 m s^{-1}. The results are summarized in Table 1, where columns 6 and 7 list the ranges of percentages of correctly dealiased or de-flagged data points and remaining flagged data points with respect to the total number of raw data points in each volume, respectively, for all the volumes listed in column 4. As shown by the last column of Table 1, there is no falsely dealiased or de-flagged datum at any of the 10^5-10^6 data points in each volume for all the volumes so far tested. As shown in column 6, the dealiased data coverage can be as low as 50% for a rainstorm. Note that the raw radial-velocity data collected from a rainstorm are often scattered and cover less areas than that covered by the data collected from an ice storm. The number of semi-qualified circles (selected under the two data-coverage conditions described in section 3b of XN12a) is thus often reduced and so is the dealiased data coverage for a rainstorm.

Table 1. Summary of results for the AR-Var-based dealiasing tested with severely aliased velocity data collected from the KTLX (WSR-88D radar) using VCP31 (with v_N < 12 m s^{-1}) and from the FAA's TOKC (TDWR radar near the Oklahoma City Airport) using scan Mode80 (with v_N < 15 m s^{-1}).

Event	Time period	Radar	Volumes	Scan mode	Correctly dealiased	Remaining flagged	Falsely dealiased
Ice storm	070311 – 235045 UTC 12/16/2008	KTLX	104	VCP31 v_N < 12 m s^{-1}	80-90%	10-20%	0
Ice storm	090508 UTC 1/26/2009 – 135514 UTC 1/27/2009	KTLX	182	VCP31 v_N < 12 m s^{-1}	80-90%	10-20%	0
Rainstorm	000356 – 055736 UTC 05/20/2010	TOKC	70	Mode80 v_N < 15 m s^{-1}	50-90%	10-50%	0
Rainstorm	180345 – 235910 UTC 05/24/2011	TOKC	57	Mode80 v_N < 15 m s^{-1}	50-80%	20-50%	0

The new AR-Var-based method was compared with the previous VAD-based methods. As shown in Table 2, the method outperforms the AR-VAD-based dealiasing method not only for VCP31 but also for other scan modes (with $v_N > 18$ m s^{-1}) that did not fail the latter. However, as the new method costs triply more CPU time, it is used adaptively for VCP31 with WRS-88D and Mode80 with TDWR only. This new adaptive dealiasing method was incorporated into the radar velocity data quality control package for operational tests and radar data assimilation applications at NRL and NCEP.

Table 2. Comparisons of the new AR-Var-based method (XN12b) with the two previous dealiasing methods: the AR-VAD-based method (X11a) and the three-step method (Gong et al. 2003). The performance scores listed in the last four rows are obtained for each volume (below z = 10 km) that contains the tilt selected in each case (see the referred figure). All the three methods were originally developed for operational applications to radar data assimilation, so they are completely free of human adjustment during the dealiasing procedure.

Dealiasing Method	AR-Var-based method of XN12b	AR-VAD-based method of X11a	Three-step method of Gong et al. (2003)
Analysis used for reference check	AR-Var (XN12a)	AR-VAD (Xu et al. 2010)	Modified VAD (Tabary et al. 2001)
Scores for the ice storm case in Fig. 2 of XN12b	Correctly dealiased: 88.3% Remaining flagged: 11.7% Falsely dealiased: 0	26% 42% 32%	48% 15% 37%
Scores for the hurricane case in Fig. 4 of X11a	Correctly dealiased: 83.6% Remaining flagged: 16.4% Falsely dealiased: 0	72% 28% 0	80% 3% 17%
Scores for the squall-line case in Fig. 5 of X11a	Correctly dealiased: 90.3% Remaining flagged: 9.7% Falsely dealiased: 0	86% 14% 0	98.6% 1.3% 0.1%
Scores for the cold-front case in Fig. 6 of X11a	Correctly dealiased: 88.2% Remaining flagged: 11.8% Falsely dealiased: 0	71% 29% 0	98.8% 1.2% 0.001%

The performance of the upgraded continuity check (Xu et al. 2012c) is shown by the example in Fig. 1. If the original block-to-point continuity check is used, then most data around the tornado-generating mesocyclone (marked by the yellow circle in Fig. 1b) will remain flagged (not shown).

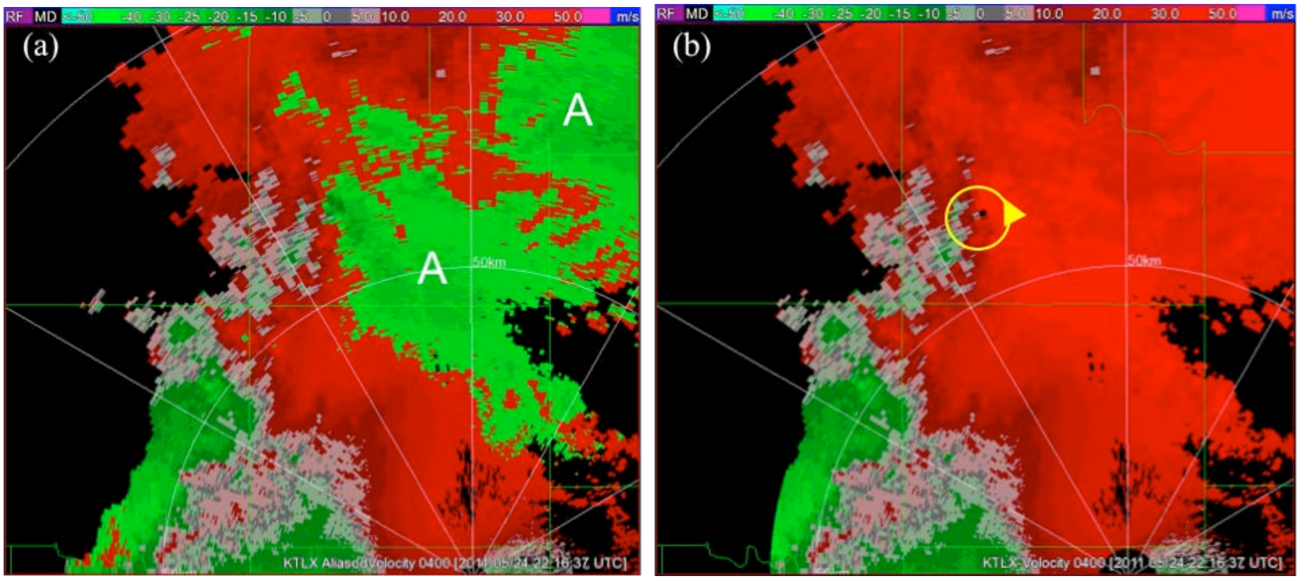

Fig. 1. (a) Raw radial-velocity image scanned by the KTLX radar with v_N = 26.1 m s^{-1} at 4.0^o tilt for a tornadic storm at 221637 UTC on 24 May 2011. (b) Dealiased radial-velocity image by the upgraded method. The two white letters "A" mark the main aliased-velocity areas in panel (a). The yellow circle with an arrowhead in panel (b) marks a tornado-generating mesocyclone.

For the tornadic storm in Fig. 1, the background wind field (Fig. 2a) was obtained from the operational RAP forecast in step-I of the three-step analysis in the upgraded RWAS (Xu et al. 2012c), while the analyzed wind field (Fig. 2b) was produced efficiently in step-III by using super-observations generated by combining dealiased radar velocities scanned from five operational WSR-88D radars in three batches with the resolutions coarsened to 30, 21 and 13 km (in both the radial and azimuthal directions), respectively, over the far (r > 80 km), middle (40 km < $r \leq$ 80 km) and near ($r \leq$ 40 km) radial ranges from each radar. The background error de-correlation length L was set to 25, 18 and 11 km consecutively when the analysis is updated serially with the three batches. Although the super-observation resolution (13 km) for the third batch was compatible with the de-correlation length (L = 11 km) in terms of minimizing information loss (Xu 2011), this resolution was too coarse to resolve the tornadic mesocyclone (marked by the small yellow circle in Fig. 2b). This explains why the analyzed winds in Fig. 2b were merely deflected and curved around the tornadic mesocyclone (in comparison with the background winds in Fig. 2a) but still too smooth to resolve the mesocyclone.

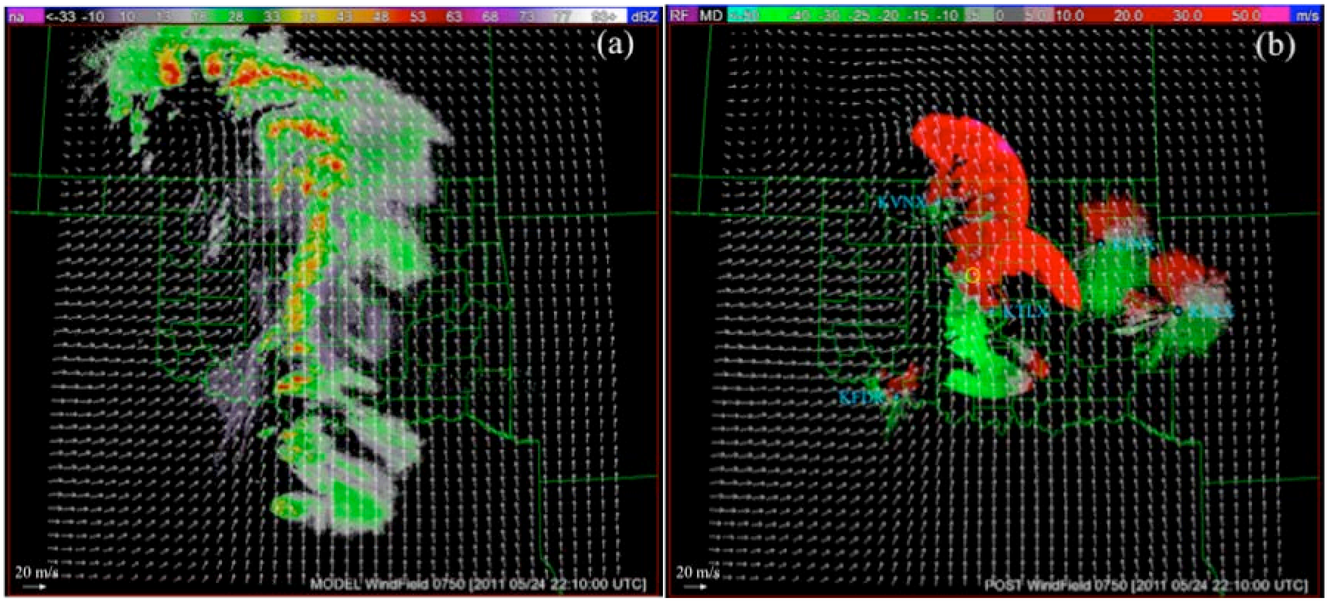

Fig. 2. (a) Background wind field at z = 0.75 km from the operational RAP forecast superimposed on the combined reflectivity image from five radars for the same storm system at the same time as shown in Fig. 1. (b) Analyzed wind field at z = 0.75 km superimposed on the dealiased radial-velocity images at 4.0^o tilt from KVNX and KTLX, 0.9^o tilt from KFDR, and 0.5^o tilt from KINX and KSRX radars. The image from KTLX is on the top of that from KVNX and each radar site is marked by a blue dot with the radar name in panel (b). The small yellow circle in panel (b) marks the same tornado-generating mesocyclone as marked in Fig. 1b. The analysis domain is centered at the KTLX radar. The domain size is 800×800×5 km^3 with resolutions of $\Delta x = \Delta y = 5$ km and $\Delta z = 250$ m.

To resolve the tornadic mesocyclone, an additional step of analysis was performed by using the vortex wind analysis scheme described in the previous section. The analysis was performed with the background error covariance matrix constructed analytically by a flow-dependent correlation function (multiplied with the background error variance estimated from observation innovations) in a moving coordinate system following the tornadic mesocyclone. The flow-dependent structures of the background correlation for stream-function are plotted in Fig. 3a by the green, black and brown contours with respect to the selected points A, B and C, respectively. The vector winds produced by the vortex wind analysis is plotted at z = 4km in Fig. 3b, while the analysis domain size is 10×10×5 km^3 and this domain is nested into that in Fig. 2b and co-centered with the mesocylone at each vertical level. The vortex wind analysis is not only very effective but also efficient in retrieving the intense vortex flow around such a mesocylone.

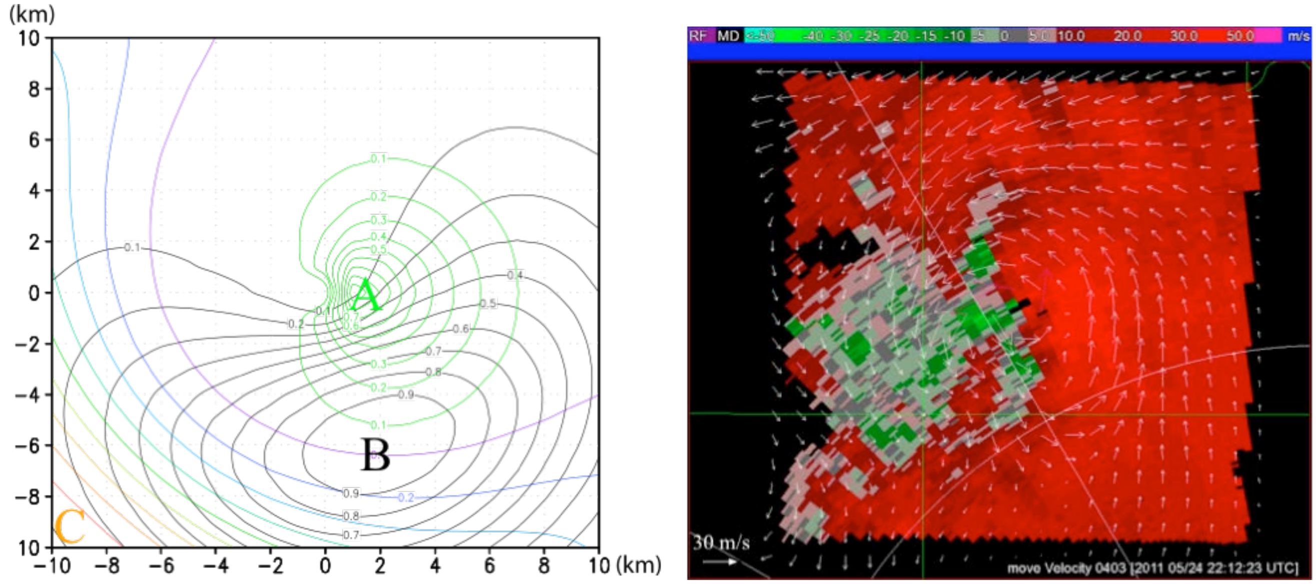

Fig. 3. (a) Structures of background correlation for stream-function plotted by green, black and brown contours relative to the selected points A, B and C, respectively. (b) Vector winds produced by the vortex wind analysis plotted at z = 4 km and superimposed on the dealiased radial-velocity image at 4.0° tilt from KTLX. The analysis domain (10×10×5 km³) is co-centered with the mesocylone at each vertical level.

IMPACT/APPLICATIONS

Fulfilling the proposed research objectives will improve our basic knowledge and skills in radar data QC and assimilation, especially concerning how to optimally utilize rapid-scan radar observations to improve numerical analyses and predictions of severe storms and other hazardous weather. New methods and computational algorithms developed in this project will be delivered to NRL Monterey for operational tests and applications.

TRANSITIONS

The radar data QC package developed in this project will be delivered to NRL Monterey for operational tests and applications. The QC package will be also made available to NCEP for operational applications. Based on the feedbacks from NRL and NCEP, the code will be upgraded and delivered subsequently. The previously developed radar data assimilation package (delivered to NRL for nowcasst applications) will be combined with the time-expanded sampling algorithm (Xu et al. 2008a,b; Lu et al. 2011) for ensemble-based filters and used, in collaboration with Dr. Alan Q. Zhao at NRL Monterey, to develop improved Doppler radar/satellite data assimilation capabilities at NRL Monterey.

RELATED PROJECTS

"Ensemble assimilation of Doppler radar observations" (funded by ONR to NRL Monterey).

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